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NFF Special Session - Potentials of Applying Methods, Tools, Processes and Knowledge from Testing in Product Development to the NFF Problem

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Abstract

While verification is an important and expensive task in the development of airborne systems, insights gained into the system under test are still very much treated in an isolated way. This means that the knowledge established in the testing of airborne systems in product development is currently not applied to e.g. repair or maintenance processes. This raises the question, whether the methods, tools and processes as well as the knowledge which is generated during testing are exploitable in the following life cycle phases, especially for service and maintenance processes? This paper presents a vision and investigates the potentials of how the methods, tools, processes and knowledge used during the verification phase in the beginning of life of an airborne system could be utilized in later lifecycle phases. A special emphasis is placed on how they can be applied to improve repair and maintenance activities in the context of NFF (No Failure or No Fault Found) cases (and vice versa). It can be expected that the methods, tools, processes and knowledge could be valuable for reducing ground times of aircraft, minimizing repair costs, reducing efforts for failure analysis considerably and improving aircraft safety.

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Keywords: NFF, System verification, testing, repair, maintenance, service, product lifecycle

1. Introduction

The aviation sector is well-known for safety-critical systems. Whilst aircraft systems undergo extensive testing in the Beginning-of-Life (BoL) of their lifecycle to ensure their safe and reliable operation, little use is made of the methods and tools used or the knowledge created in those processes in the other lifecycle phases Middle of Life (MoL) and End-of-Life (EoL). This paper investigates how these can be applied to the No Failure Found (NFF) problem in aircraft MoL, which is *"... an age-old phenomenon that strangely enough has not yet been entirely successfully solved..."* [1]. Whilst the authors are aware of activities such as ARINC 672, their contribution aims to stimulate discussion on using testing methods, tools and knowledge in other application areas. In order to limit the scope, the authors concentrate on high lift system testing. The paper commences with a general introduction to high lift systems. Then, the testing process and the methods and tools applied are discussed. Subsequently, the main challenges for high lift system testing are described. After thus establishing an understanding of testing, the next sections investigate how to apply them to help solve NFF. Here, organizational and economical foundations, technologies and obstacles are discussed. The paper concludes with suggestions for next steps for the utilization of testing methods, knowledge and tools.

2. High lift systems

High lift systems [2] are an aircraft component which allow the reduction of speed with the simultaneous increase of lift in flight conditions such as take-off or landing, by modifying the aircraft's wing geometry using moving surfaces – so-called flaps and slats. The wing area and deflection is increased to reduce the speed of the aircraft while keeping it in the air. The system is controlled from the cockpit by the flaps lever. The lever position is communicated to the Slat Flap Control Computer (SFCC), along with other parameters like speed, angle of attack, etc. For redundancy reasons there are two

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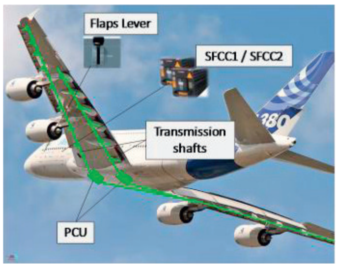

Figure 1: The high lift system of the A380

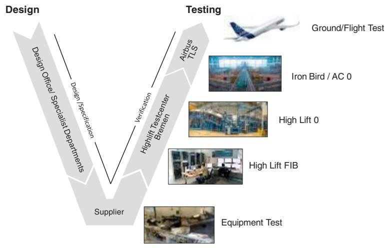

Figure 2: Process for high lift testing

SFCCs in the aircraft (SFCC1 and SFCC2). The SFCC controls the Power Control Unit (PCU) which is connected to the transmission shafts. The transmission shafts move the flaps and slats. The SFCC monitors the process to ensure no failure which could result in a critical situation occurs. For example, a mechanical problem, like a transmission shaft breaking, causes the SFCC to stop the PCU immediately to avoid asymmetric wing profiles caused by flaps or slats at different positions on both wings. The components are shown in Figure 1. Due to its central role in takeoff and landing, the high lift system is a safety-critical component which has to be tested carefully in order to ensure its safe and reliable function. High lift systems are becoming more and more complex to meet demands such as better fuel efficiency or noise emission reduction. Multifunctional solutions are in development such as the “Advanced Dropped Hinge Flap” (ADHF), invented and patented by Airbus for the A350 XWB. Although simpler and lighter than a conventional flap, it requires close cooperation between different parts of flight control, because flap movement is always accompanied by the spoiler. The high lift system is part of the secondary flight control system, but the spoiler belongs to primary flight control. When closing the gap between the trailing edge of the wing and the flap by the spoiler both control systems have to communicate and interact. The trade-off for reduced mechanical complexity is paid here by more complex control solutions implemented in the involved control computers.

3. Testing high-lift systems

The following sections describe the methods, tools, and processes applied in testing high-lift systems and indicates what kind of knowledge is generated.

3.1. High lift processes and test means

High lift systems need to be carefully tested before a new aircraft’s maiden flight. Different levels of testing are carried out, each requiring different test means. Depending on the stage of development, these test means get closer to the final (real) system which will be integrated into the aircraft. The underlying strategy is straightforward: It intends to shift testing activities downstream to test means that are already available early in the development process in order to detect the need for further development of failures as early as possible. Figure 2 shows test means and their relationship to the development process. The development process follows the V-Model [3] with the system design and specification on the left. Development ends with the realization of the system by the supplier. The right hand side covers the test phases associated with the development phases on the left. The idea is to achieve a high test coverage, because the specifications of each development step on the left form the basis for the test cases of the corresponding test activities on the right. In general, the functional and first integration testing is done by the supplier in their part/component development process. After that, the integration tests are done by Airbus. Initial testing is done on Functional Integration Benches (FIBs) which are a mixture of real hardware (System under Test - SuT) and simulation models for subsystems which are not present. There are different FIBs for the various aircraft functions, such as High lift FIB or Fuel FIB. The SuT, in this case the SFCC, is tested according to the stimulation-reaction scheme which means that electrical signals are sent to the SuT and its reaction (outgoing signals) are monitored and analyzed. The surrounding aircraft environment is simulated, so that the SuT “believes” it is operating in a real aircraft. On the next level the so-called zero-means come into play. These test rigs represent entire aircraft components, such as the Cabin zero (Hamburg) or Landing Gear zero (Filton). The High lift zero-mean (HL-0), which is located in the High Lift Test Center in Bremen, comprises all mechanical components (transmission shafts, linkages, actuators etc.) of the high lift inside the first “real” aircraft (MSN001). The name “zero-mean” (MSN000) indicates that these test rigs are built to be as close to the real system as possible. Therefore the high lift zero-rig consists of a left wing which comprises all parts and components later installed on the MSN001 aircraft. The surrounding structural parts of the wing are not present and replaced by a “blue” steel construction. The rig contains also equipment in for applying air loads to the flap. The right wing is “simulated” by a complex electro-hydraulic brake system. The rig is used to perform test cases in order to ensure the reliable and safe operation of all (mechanic and electronic) parts of the high lift system. In addition many tests can be performed which would be too dangerous for the flight tests performed by MSN001, such as transmission shaft breakages. In order to ensure the safe and reliable operation of the whole system with all major aircraft components integrated, the final “zero” integration mean was built in Toulouse. This so-called “Iron Bird” comprises the complete hydraulic, electric and flight-control system as it will be installed on the

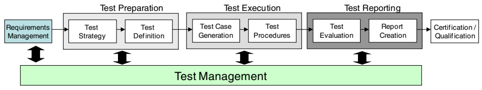

Figure 3: Main Steps

MSN0001 aircraft. The Iron Bird guarantees that the major systems are working properly with each other. The last integration testing step before flying MSN001 is the connection of the Iron Bird to the integration simulator. Here all systems are tested from the cockpit. Each activity here (e.g. moving the side-stick) is processed along the signals generated (lever position, speed etc.) and transmitted to the flight control computers which control the flight actuators. The electrical and hydraulic power taken by the actuators is also delivered from components within the Iron Bird which are exactly the same as those on the MSN001. In this phase the flight test pilots are already involved in the testing process. The safe operation of all parts is continued during the ground test performed with the MSN001 aircraft. After that flight tests will be performed. The parameters gained here are further analyzed by the high lift test engineers to ensure whether the high lift system works as expected and the main air load parameters are as expected.

3.2. Methods and software tools

When testing on FIBs or high lift test rigs test engineers follow a pre-defined process with three main steps (see Figure 3) for test preparation, test execution and test reporting. The overall test process is planned during Test Preparation. Test categories are determined and their processing scheduled. This is important to ensure the availability of test means for test execution. Based on the resulting plan, test definitions are specified in a non-standard way (plain text). Test definitions comprise initial conditions and the course of a certain test aspect which is reflected by the change of involved system parameters. Whether a test fails or passes is determined in the course of test execution based on the value of certain system parameters at certain points in time. As test definitions are always elaborated against specific system requirements, it is important to establish a link between them to be able to assess which requirements have or have not been considered during the overall testing process. This is critical for predicting the completion and tracing the progress of the test process. During test execution the test definitions are transformed into test procedures. These are formal representations of test definitions, which are then translated into executable files to be executed on the FIB afterwards. During test procedure execution, test data is monitored, visualized and stored for later analysis and test reporting. Data generated in test case execution is evaluated against whether it lies within the expected value range. Furthermore, the test process is documented in detail and provided to the authorities responsible for the certification/qualification of the SuT. All of these steps are usually organized and supported by a tool chain integrated into a Test Management tool. The High Lift Test Center uses the ITE (Integrated Test Environment) tool [4] which allows a high degree of automation of costly activities, saving not only time and money but also improving the overall test quality, because

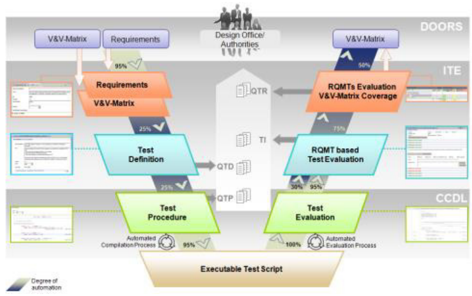

Figure 4: High Lift Test Center test methodology in detail

specific error-prone tasks are not subject to human error. The test methodology shown in Figure 4 is fully supported by ITE. First of all the requirements are imported from well-known tools, such as DOORS. In addition, the V&V matrix from the design office is imported. This describes which means have to be applied to test a certain requirement. The V&V matrix and the requirements are both imported using standard file formats. After that test definitions are developed in a specific view of the ITE. These test definitions anticipate the real-life operation of the SuT by playing through all of the scenarios which might occur in operation. Test systems are also applied to evaluate scenarios that would be too dangerous for flight tests with a real aircraft. Requirements and related constraints for testing are already known by the system and can be easily applied for the creation of test definitions, because they have previously been imported into the internal database. Test procedures are then created based on test definitions using the high-level language CCDL (Check Case Definition Language) [5]. It is easy to learn and expressive enough for the authorities to accept test procedures written in CCDL as part of the mandatory documentation for certification. ITE can offer tailored views for the creation of test procedures to the test engineer, because all relevant parameter names (representing flight and system data) are already known by the system. Next, the test procedures written in CCDL are translated into native test procedures that can be executed on the FIB and controlled remotely by the test engineer. During execution, test data and test step status (pass or fail) are recorded by the system. Test evaluation is mainly done automatically based on data gathered during test execution and under consideration of the conditions specified within each test procedure such as expected system parameter values in specific situations or within certain time intervals. Then, the internal database of ITE is updated whereas the tests and their results are linked to their associated requirements. Finally, all of the test cases, their results, the associated requirements as well as the applied test means are consolidated in the internal database. Any changes for test means that have been used for test execution are communicated to the design office in order to modify the V&V accordingly. Mandatory documents required by the authorities for certification are generated by ITE at every step of the methodology.

3.3. Main challenges for testing

The biggest challenge for testing is the continuous improvement of high lift systems, for instance, the introduction of ADFX in A380, auto functions in A400 or multi system functions required by ADHF for A350. The consequent increase in system complexity is mirrored in an increased effort for testing. Figure 5 indicates the increasing complexity over the course of the advancement of high lift systems. Compared to A380 almost three times more interfaces parameters have to be considered for testing the A350 system. The number of system requirements is about 70% higher for A350 than for the A380. Figure 5 also shows how the technological progress affects testing. The number of test cases required for certification has risen by a factor of 3 from A380 to A350. Even more challenging is that testing usually starts at a late phase of the development process, when the supplier of the SuT delivers the first prototype. Although some components can be simulated for first insights into the system to be tested (further elaborated by Virtual Testing) the most testing activities are functional testing using a black box approach. This means the SuT is tested along the stimulus-reaction scheme without considering its internal implementation. While doing that test engineers have to anticipate the later operation of the SuT under real-life conditions. Anticipation is the base for the test plan as well as for deducting relevant test definitions. To do this efficiently requires deep knowledge and technical understanding of the SuT and its interaction with other systems in the aircraft. To keep the schedules resulting from decreasing development times the efficiency of testing has been increased considerably by the methods and tools described. Although they allow for a higher degree of automation throughout the entire test process, they are designed to support, not replace, test engineers, especially regarding test definition. The creativity and sensibility of experienced human experts are important for developing safe and reliable airborne systems.

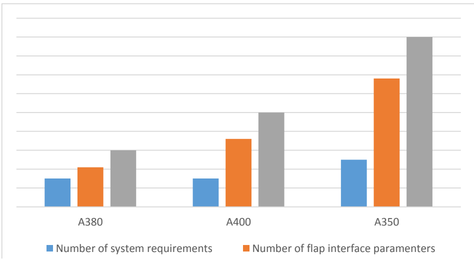

Figure 5: High lift system complexity and increasing test effort

4. Exploiting testing knowledge for NFF

The test process described above is done for the certification of the high lift system. Although the methods, tools and knowledge are still available after certification, they are only later used for minor changes to the system. The existing knowledge is applied to test upcoming innovations or for next generations of high lift systems. Unfortunately this doesn't hold true for the technical equipment due to the lack of standards [6]. This raises the question whether and how the methods, tools and the test engineers' knowledge can be applied for problems occurring later in the SuT`s lifecycle (e.g. the Slat Flap Control Computer)? The following sections deal with the potentials of these elements of testing for maintenance with a focus on the NFF. In avionics a NFF is defined by ARINC 672 as "…*the result of testing when a unit removed as faulty at one level of maintenance is found to be fault free when tested at the next lower level of maintenance*." [7] To come to a first estimation of whether and how the testing knowledge, processes and tools described above can help alleviate NFF, in the following sections, first the relevant stakeholders and their intentions are analysed. Then, general requirements and conditions are identified in order to derive the limits for potential approaches for solving the NFF problem. Based on that, potential existing technologies which could be applied to the problem field are analysed. Organizational aspects are then discussed.

4.1. Stakeholders

The airframer (i.e. the airframe builder, e.g. Airbus) provides documentation on when and how to perform maintenance and service activities to its customers. Updates to this documentation are provided as service bulletins when necessary. The airframer may receive support requests and associated maintenance data from the airlines (the customer) to sort out findings that appear during operation. Airline operators and engineers receive maintenance records and performance data from the fleet aircraft at regular intervals during flight from the on-board monitoring systems. This information is used to plan maintenance activities under consideration of maintenance capacities and part availability. Furthermore, engineering support is provided based on field data recorded by control computers on the aircraft. Line maintenance activities are performed based on the maintenance status provided by the aircraft whereas all maintenance actions done here are documented in the aircraft's logbook. The same holds true for flight operation activities taking place during normal operation for minor repairs. In the course of shop maintenance activities unserviceable Line Replacement Units (LRU) delivered form line maintenance are tested, calibrated, repaired or updated. Shop maintenance also delivers serviceable LRUs for replacement to the line maintenance. Unserviceable Shop Replacement Units (SRU) are delivered to the equipment

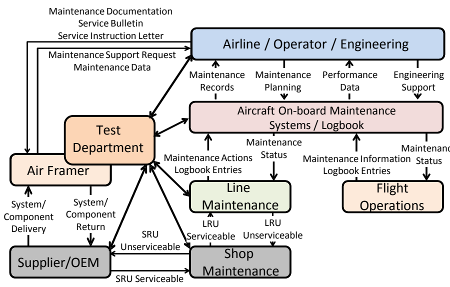

Figure 6: Extended stakeholders network in aircraft MoL

supplier for testing, repair, update or calibration while receiving serviceable SRUs that are provided by the supplier for replacement. The delivery of components or systems from suppliers to the airframer was omitted here because these activities belong to BoL. Following the vision of deploying methods, tools and knowledge gained during testing, an extension of the stakeholder network of aircraft MoL is suggested in Figure 6. The basic idea is to establish information links between the stakeholders to enable the test department to support the elimination of NFF actively in communication with all relevant stakeholders. The suggested extended stakeholder network is restricted to information exchange and does not represent any technical implementation.

4.2. General conditions

A number of issues need to be taken into account when considering the application of testing methods, tools and knowledge to subsequent lifecycle phases. First of all, *organizational issues* mainly have to be considered for stakeholders belonging a single enterprise. The exchange of information proposed in Figure 6 has to overcome existing (department) barriers which are caused by separated areas of responsibilities. For stakeholders belonging to different entities, *legal issues* need to be reflected with respect to. Intellectual Property Rights (IPR). In order to apply knowledge or tools from testing to the NFF problem it needs to be clear which information can be provided to which stakeholders under which conditions and how it can be applied. Vice-versa, the conditions for the transfer of field data from aircraft have to be regulated (ownership). Finally, agreements are required for the ownership of knowledge which is gained by applying testing knowledge to NFF problems. Extending the field of activity of testing departments from BoL to MoL introduces new responsibilities and efforts, resulting in the need to consider *economic issues*. To establish sustainable structures supporting the whole lifecycle of aircraft (usually 30 years) successful business needs to be developed and introduced into the market. However, as technical improvements (fuel consumption, noise emissions) are naturally expected by customers, significant potential for a further development of an airframer's market position can be seen by new services to the customer in order to reduce their costs, such as for reducing the NFF problem. The main challenges regarding *technical issues* come from the need to establish concepts and approaches to integrate heterogeneous IT environments found at the involved stakeholders. In addition to different platforms, various data structures and proprietary file formats have to be integrated. When discussing technical issues it should be kept in mind, that solutions that require significant adaptations won't find acceptance by the stakeholders. *Security issues* are also of importance. In general findings of any kind and particularly those related to NFF may attract attention which may cause a negative effect on a company's image. In general this kind of data, information and knowledge is critical and requires secure approaches for it not to get into the wrong hands. Approaches addressing organizational, legal, economical, security as well as technical issues have to be considered equally in the development of efficient and broadly accepted environments to address the NFF problem. Keeping in mind the conditions described above the following section will give an overview about existing technologies supporting the vision of this paper.

4.3. Existing technologies

The next sections discuss how existing knowledge, tools and processes from testing can be applied to address NFF along the following high-level requirements exists:

(1) access to and analysis of test data and knowledge bases,
(2) secure communication channels between the stakeholders,
(3) storage of NFF knowledge,
(4) *integration of heterogeneous data, information and knowledge*, and
(5) *management of roles and rights*.

4.4. Test data and knowledge access and analysis

Two types of test data relevant to the NFF problem need to be processed. First, *unstructured test data* which is generated during FIB or zero test means test execution. It consists of parameter values which change over execution time. A significant amount of this data is generated and archived during test execution. Due to its volume, unstructured test data requires intelligent filters, data mining and "big data" analysis approaches to be applied to NFF diagnosis. Secondly, *structured test data* in the form of test means configuration files and test procedures written in high level languages such as CCDL. Knowledge Management (KM) approaches are applicable here. Because of the formal nature of structured test data, tools e.g. from compiler construction can be used for semantic analysis to support other KM approaches for classification etc. Other suitable methods within Artificial Intelligence (AI) are formal reasoning approaches like Expert Systems, which can solve complex problems by emulating human decision-making abilities based on a system of rules and a fact base describing the problem domain. This is done by an inference engine which can reason over the knowledge base. Another suitable AI solution is Case-Based Reasoning (CBR). Here, a given problem is solved by scanning a case memory comprising all previously solved problems. In CBR a solution is found by applying the solutions of former problems to the current one. For both approaches, a knowledge base has to be established and maintained which requires significant effort. Both approaches can significantly shorten the time for finding NFF solutions and could reduce costs considerably.

4.5. Secure communication channels between the stakeholders

The Node-Controller (NC) developed in the research project BreTeCe [8] is a specific approach secure communication channels between stakeholders in testing. The NC enables the interconnection of test components which are physically distributed to a joint virtual test environment. A "virtual cable" is represented by (at least) two NC each of which is assigned to the subsystem to be interconnected. Test signals are securely transmitted from one subsystem to another by communicating via the Internet. Furthermore, the NC allows centralized configuration, health monitoring of the complete network and control of distributed test execution. Including another subsystem into such a distributed testing network is easy and only requires another NC. The NC technology is currently under evaluation by Airbus to interconnect test means from different sites. In December 2012 the high lift zero test mean in Bremen was successfully connected to the virtual cockpit which is located in Toulouse.

4.6. NFF Knowledge Storage

When solving NFF problems, knowledge about the reasons for the problem as well as actions carried out afterwards should be documented, archived and shared amongst relevant stakeholders to re-utilize this knowledge for future solution finding. A specific knowledge base should be established based on existing KM technology. The main reason for the introduction a dedicated KM system shared by all stakeholders is to overcome integration barriers resulting from the stakeholders' heterogeneous IT architectures. An open question is the responsibility for a shared NFF KM system. Either the system can be managed by the airframer for all NFF affecting a certain aircraft type or the supplier of the system causing the NFF. Last but not least, an external neutral facility could take responsibility for such a KM system.

4.7. Secure management of roles and rights

This general requirement is addressed by all of the technologies discussed. Existing solutions usually don't offer components for the management of roles and rights at the same functional level. Although appropriate concepts (e.g. single-sign-on) and solutions are available, they usually require significant integration efforts. From that point of view it has to be decided from case to case which support level is sufficient enough to ensure security while exchanging data, information and knowledge to address the NFF problem.

4.8. Integration of heterogeneous data, information and knowledge

A significant barrier in establishing lifecycle-wide, multi-stakeholder collaboration and knowledge exchange is the integration of the heterogeneous IT systems of the participants. Whilst this is a general problem in closed-loop PLM for all sectors, the problem is exacerbated in avionics and particularly in testing, because very specific and proprietary systems, data formats and interfaces are employed. Furthermore, the need to exchange highly specialized data and knowledge across department and organizational borders can lead to semantic conflicts – in this case, the meaning of data and knowledge from testing could be misinterpreted in maintenance. In order to manage both the challenge for data integration and to avoid semantic interoperability conflicts, semantic approaches to data integration are required. One such approach, semantic mediation [9], has successfully been shown to complex data semantic integration problems in logistics, closed loop PLM problems and could be considered here.

5. Conclusions

In response to the question of whether testing tools, methods, processes and knowledge be applied to NFF, it can be said that valuable knowledge for the problem is generated in testing. Furthermore, most of the required technology is already available. However, integrating all of the components into an infrastructure which fulfills the requirements could be challenging. There is currently no off-the-shelf solution from the testing arena which could be directly applied to tackle the NFF problem. The most critical points are the legal issues and the lack of sustainable business models. Concerning legal issues in particular the ownership and the usage of testing and NFF knowledge needs to be regulated. Sustainable business models need to be developed and introduced into the market in order to operate the technical infrastructure. A more general aspect is the general willingness to cooperate in the aviation sector. As new services become more and more important for airframers to strengthen the position in global markets it can be assumed that they will establish networks not only for aircraft BoL but also for MoL and EoL. Concerning the next steps, solving legal issues has to be considered the first priority. In addition, technical approaches have to be integrated into a flexible infrastructure fulfilling the presented requirements. This has to be done while addressing business models to keep the infrastructure running for the entire aircraft lifecycle.

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